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Behaviour of RC slabs flexurally strengthened with prestressed NSM CFRP laminates

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SUMMARY
To investigate the effect of the prestressed NSM CFRP laminates on the behaviour of RC slabs, an experimental program was carried out. A total of four RC slabs were tested, a reference slab (without CFRP), and three slabs flexurally strengthened using NSM CFRP laminates with different prestress level: 0%, 20% and 40% of the ultimate tensile strength of the CFRP material. The experimental program is described and the main results are presented and analyzed in terms of the structural behaviour of the RC slabs, failure modes and performance of the NSM technique with prestressed CFRP laminates.

1. INTRODUCTION

Near surface mounted (NSM) with carbon fiber reinforced polymer (CFRP) laminates is a technique that can be used for the flexurally strengthening of reinforced concrete (RC) elements. This technique involves the installation of narrow strips of CFRP laminates, of rectangular cross section, into thin slits open on the concrete cover of the tensile zone of RC elements. The laminates are bonded to concrete by an epoxy adhesive.

The efficacy of the NSM strengthening technique with passive CFRP laminates to increase the flexural resistance of RC beams [1-5] and slabs [6] was already well assessed. In fact, NSM CFRP laminates without any prestress level can increase significantly the ultimate load carrying capacity of RC structural elements. However, for the deflection levels corresponding to the serviceability limit states this increase is, in general, of small relevance. To obtain a significant increment in terms of load carrying capacity for these deflection levels, prestressing the CFRP is a suitable solution. By prestressing the CFRP, its high tensile capacity is more effectively used, contributing to increase significantly the load carrying capacity of the strengthened elements under both service and ultimate conditions. The prestress can also contribute to close eventual existing cracks, and to increase the shear capacity of these elements.

In this study, the effectiveness of the NSM technique with prestressed CFRP laminates for the flexurally strengthening of RC slabs is assessed. Four RC slabs were executed with the purpose of evaluating the influence of the prestressed level in the behavior of this kind of structures in terms of serviceability and ultimate limit states. A detailed description of the carried out experimental research, and a discussion of the obtained results are done in the present paper.

2. EXPERIMENTAL PROGRAM

2.1 Test series, test set up and monitoring system

The experimental program is composed of four RC slabs with a cross section of 120×600 mm^2 and a span length of 2400 mm. The longitudinal steel reinforcement is consisted of 3 bars of 6 mm diameter (3ϕ6) in the compression zone and 4 bars of 8 mm diameter (4ϕ8) in tension surface. Steel stirrups of 6 mm diameter spaced at 300 mm (ϕ6@300mm) are adopted for transversal steel reinforcement. The adopted reinforcement systems were designed to assure flexurally failure mode for all the tested slabs. Fig. 1 represents the cross section geometry and reinforcement detailment for each slab, as well as the longitudinal geometry, loading configuration and support conditions. The concrete clear cover of the longitudinal tensile bars is 20 mm.

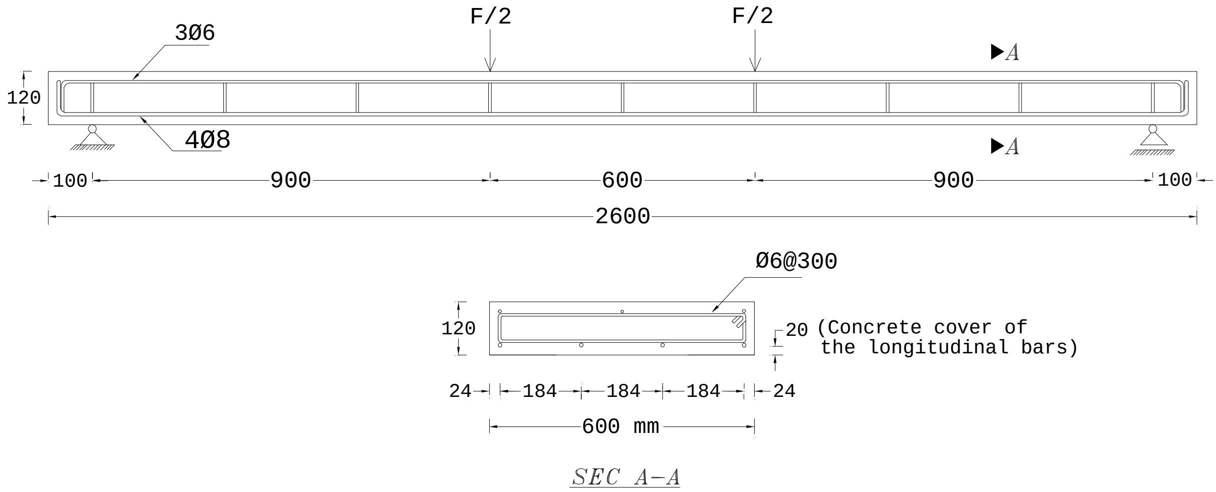


Figure 1: General information about the tested RC slabs (dimensions in mm).

The general information of the four tested RC slabs is represented in Table 1. The SREF is the reference slab without CFRP, and the S2L-0, S2L-20 and S2L-40 slabs are those flexurally strengthened using two NSM CFRP laminates (Fig. 2) with different prestress level: 0% (S2L-0), 20% (S2L-20) and 40% (S2L-40) of the ultimate tensile strength of the CFRP laminates. The CFRP laminates used in the present experimental program have a cross section of 1.4 (thickness)×20 (depth) mm^2. Table 1 shows that the tested slabs have a percentage of longitudinal tensile steel bars (ρ_{sl}) of about 0.35%, while the CFRP strengthening percentage (ρ_f) is approximately 0.08%.

Table 1: General information about the tested RC slabs.

Slab	ρ_{sl} [%] (1)	NSM CFRP flexural strengthening		Level of prestress (%)
		Quantity	ρ_f [%] (2)	
SREF	0.349	-	-	-
S2L-0		2 CFRP laminates with 1.4×20 mm^2 of cross-section ($A_f = 2\times1.4\times20 = 56\ mm^2$)	0.077	0
S2L-20				20
S2L-40				40

(1) The percentage of the longitudinal tensile reinforcement was obtained from $\rho_{sl} = \left(A_{sl} / (b_w \times d)\right) \times 100$, where A_{sl} is the cross sectional area of the longitudinal tensile steel reinforcement (see Fig. 1), b_w = 600 mm is the width of the slab, and d is the distance from extreme compression fibre to the centroid of tensile reinforcement. (2) The CFRP percentage was obtained from $\rho_f = \left(A_f / A_c\right) \times 100$, where A_f is the cross sectional area of the NSM CFRP flexural strengthening and A_c is the cross sectional area of the concrete.

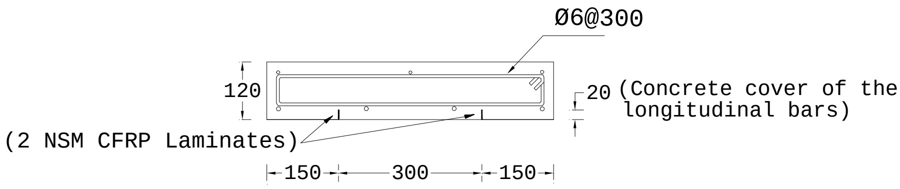


Figure 2: Cross-section of the RC slabs strengthened with NSM CFRP laminates with or without prestress (dimensions in mm).

The four point slab bending tests (Fig. 1) were executed under displacement control at a deflection rate of 0.02 mm/second. All slabs were instrumented to measure the applied load, deflections, strains in the CFRP laminates and in the longitudinal tensile reinforcing steel. Positions of the LVDTs (linear variable displacement transducers) and strain gauges in the monitored longitudinal tensile bars and in the NSM CFRP laminates are indicated in Fig. 3. The deflection of the slabs was measured by five displacement transducers (LVDT 1 to LVDT 5) according to the arrangement indicated in Fig. 3a. To evaluate the strains on the steel bars, three strain gauges were installed (Fig. 3b) on the two bottom longitudinal steel bars (SG-S1 to SG-S3). In the strengthened slabs, three strain gauges were installed on two CFRP laminates (SG-L1 to SG-L3) for evaluating the strain variation along the laminates (Fig. 3c).

2.2 Materials

The concrete compressive strength was evaluated at the age of the slab tests, carrying out direct compression tests with cylinders of 150 mm diameter and 300 mm height, according to EN 206-1 [7]. In the tested slabs, high bond steel bars of 6 and 8 mm diameter were used. The values of their main tensile properties were obtained from uniaxial tensile tests performed according to the recommendations of EN 10002 [8]. The tensile properties of the CFK 150/2000 S&P laminates were characterized by uniaxial tensile tests carried out according to ISO 527-5 [9]. Table 2 includes the average values obtained from these experimental programs.

S&P Resin 220 epoxy adhesive was used to bond the CFRP laminates to the concrete substrate. The instantaneous and long term tensile behaviour of this adhesive was investigated by Costa and Barros [10]. At 3 days, at which the elasticity modulus ($\boldsymbol{E_{0.5\sim2.5‰}}$) has attained a stabilized value, the tensile strength and the $\boldsymbol{E_{0.5\sim2.5‰}}$, determined according to the ISO 527-2 recommendations [11], was about 20 MPa and 7 GPa, respectively.

Table 2: Values of the properties of intervening materials.

Concrete	Compressive strength		
	f_{cm} = 46.7 MPa (at 294 days - age of slab tests)		
Steel	Tensile strength	ϕ6	ϕ8
	f_{sym} (yield stress)	464.0 MPa	486.0 MPa
	f_{sum} (tensile strength)	617.7 MPa	570.2 MPa
CFRP Laminates	Tensile strength	Young's Modulus	Maximum strain
	f_{fum} = 2483.9 MPa	E_{fm} = 153.2 GPa	ε_{fu} = 16.2 ‰

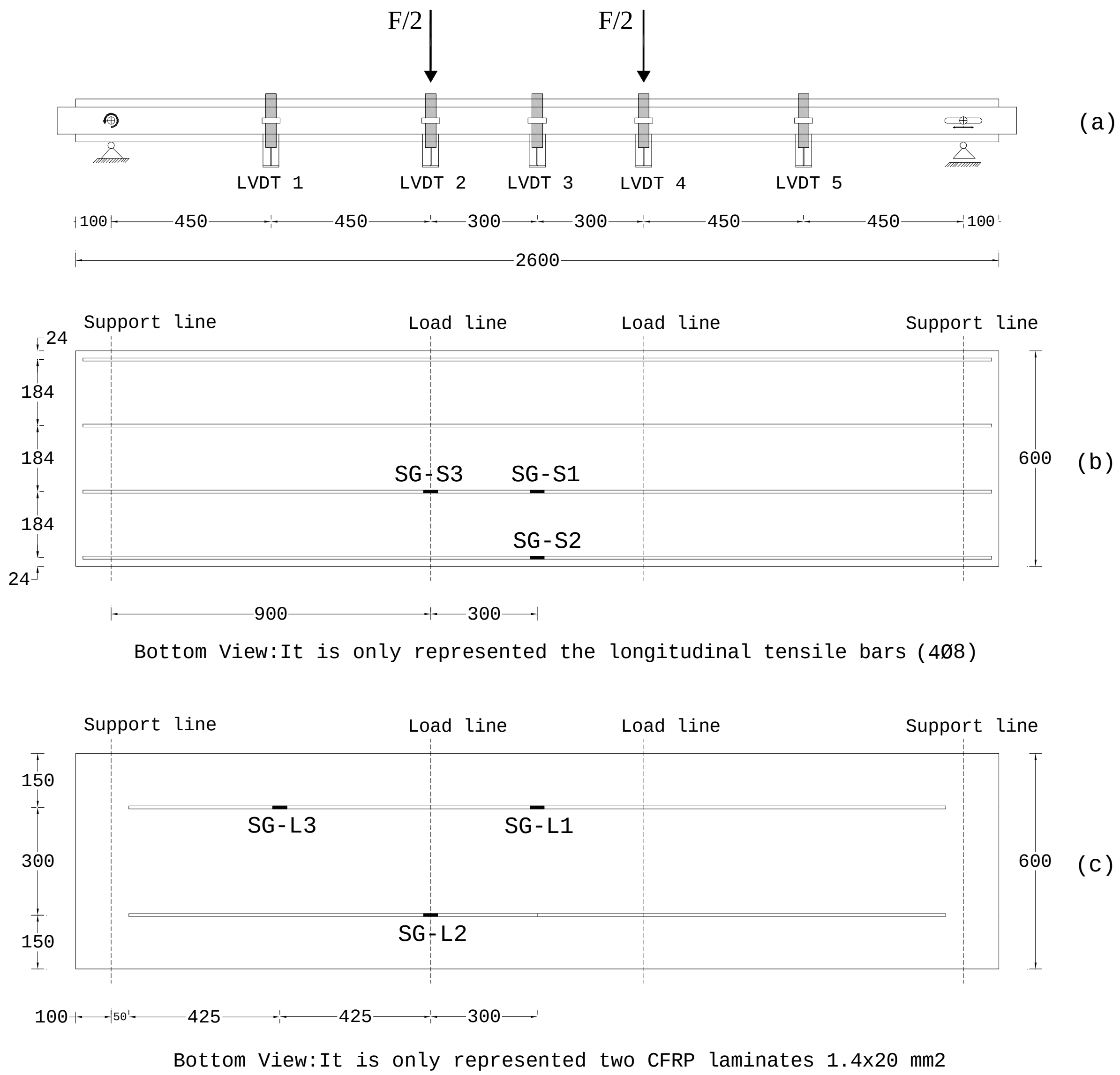


Figure 3: Positions of the: a) displacement transducers (LVDTs); b) strain gauges in the monitored longitudinal tensile bars; c) strain gauges in the NSM CFRP laminates (dimensions in mm).

2.3 Application of the NSM CFRP laminates

To apply the passive CFRP laminates using NSM technique, the following procedures were executed: 1) using a diamond cutter, slits of about 5 mm width and 25 mm depth were opened on the concrete cover of the tension face, according to the pre-defined arrangement for the laminates; 2) the slits were cleaned by compressed air; 3) the laminates were cut with the desired length and cleaned with acetone; 4) the epoxy adhesive was produced according to the supplier recommendations; 5) the slits were filled with the adhesive; 6) a layer of adhesive was applied on the faces of the laminates; and 7) the laminates were inserted into the slits and adhesive in excess was removed.

Fig. 4 shows the device for applying the prestressing force, which include the main system to apply the pressure into the hoses, handle for controlling the oil pressure, hydraulic hollow jacks for transferring force to the laminates and load cells that were installed between hydraulic jacks and main frame to control the value of prestressing load. After installing the slab in the right position of prestressing line, the CFRP laminates are put into the slits (of about 5 mm width and 25 mm depth that were previously opened on the concrete cover of the tension face) and passed through the hydraulic jacks and load cells and were anchored in both extremities by using an active and a passive anchor, as is indicated in the

Fig. 4. Each laminate was installed in the middle of the slit, as closest as possible to the slab's external surface, and then the prestressing force was applied.

In S2L-20 and S2L-40 slabs the prestressing load for each laminate was about, respectively, 20% and 40% of its tensile strength. The prestressing force was applied to one extremity of laminate by the hydraulic jack, while the other extremity of the CFRP laminates remained fixed to the main frame of prestress line by anchors. The increase of the prestressing load was about 0.5 kN/min.

When the prestressing load was completely applied to the laminates, epoxy adhesive was applied into the slits by using a spatula, as indicated in Fig. 4. After curing the adhesive (about seven days), the prestressing load was released slowly and simultaneously in both CFRP laminates at a load rate of about 0.3 kN/min.

Figure 4: Application of the prestress in the NSM CFRP laminates.

3. RESULTS AND DISCUSSION

3.1 Load carrying capacity of the tested slabs

Fig. 5 shows the relationship between the applied load and the deflection at mid-span, *F*-*u*, for the tested RC slabs. This figure shows that the experimental load-displacement curves of the slabs have three important phases, until cracking of the concrete, between concrete cracking and yielding of steel reinforcement, and between steel reinforcement yield initiation and ultimate load. As expected, the unstrengthened control slab behaved in a plastic manner in the third phase. In this last phase, curves of strengthened slabs had a linear slop due the presence of the CFRP (linear behavior of the CFRP laminates). In fact, above the load at yield initiation in the strengthened slabs the load has continued to increase until the CFRP rupture, after which the load dropped to that of the control slab. Regardless the prestress level of the laminates (0%, 20% and 40%), the adopted CFRP configuration provided an increase in the slab's load carrying capacity at serviceability and ultimate limit states.

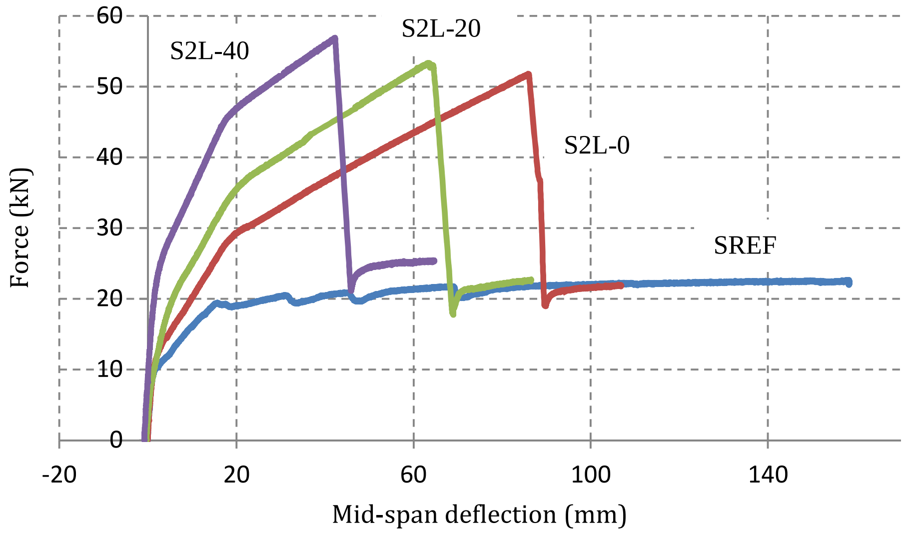


Figure 5: Force vs deflection at mid-span for the tested RC slabs.

Table 3 shows the summary of the results of the tested RC slabs in terms of service ($F_{serv.}$), yielding (F_{sy}) and maximum (F_{max}) load. The values of the deflection at mid-span for the loads $F_{serv.}$ ($\delta_{Fserv.}$), F_{sy} ($\delta_{Fsy.}$) and F_{max} (δ_{Fmax}) are also indicated in Table 3. The service load is the load corresponding to the maximum allowed deflection for serviceability limit states, which according to the Eurocode [12] is *l/250*, where *l* is the slab span length (*l*/250 = 2400 mm/250 = 9.6 mm). The yielding load is herein defined as the load at which a considerable decay of stiffness has occurred.

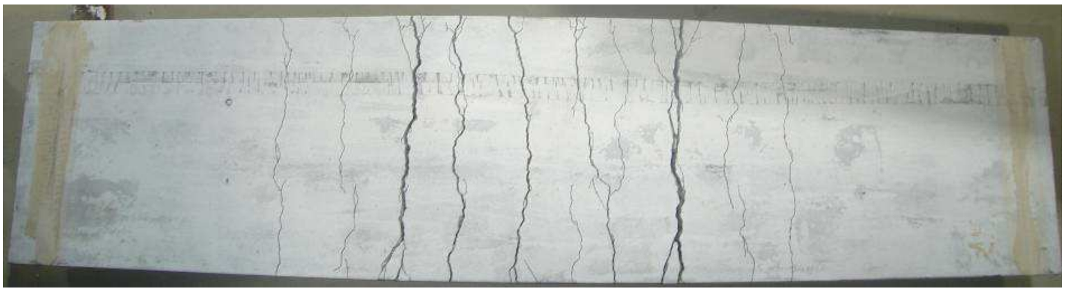
Based on Table 3, the values of service loads of reference, non-prestressed, 20% and 40% prestressed slabs are respectively, 15.89 kN, 19.76 kN, 24.65 kN and 34.76 kN, which evidence the benefits of applying the CFRP laminates with a certain prestress. The values of maximum load of strengthening slabs ranged between 51.8 kN and 56.9 kN, showing a significant improvement when these values are compared with the maximum load of the reference slab (22.6 kN). Based on these experimental results, the deflection level of maximum loads for 0%, 20% and 40% of prestressed slabs were respectively, 85.90 mm, 63.33 mm and 42.29 mm, which shows that prestressing CFRP laminates decreased considerably the deflection level corresponding to this load. Strengthening the RC slabs with NSM CFRP laminates resulted in higher yielding loads than the F_{sy} of the reference slab and with increasing the level of prestressing, yielding load increased that was indicated in Table 3.

Table 3: Summary of the results in terms of loads and deflections.

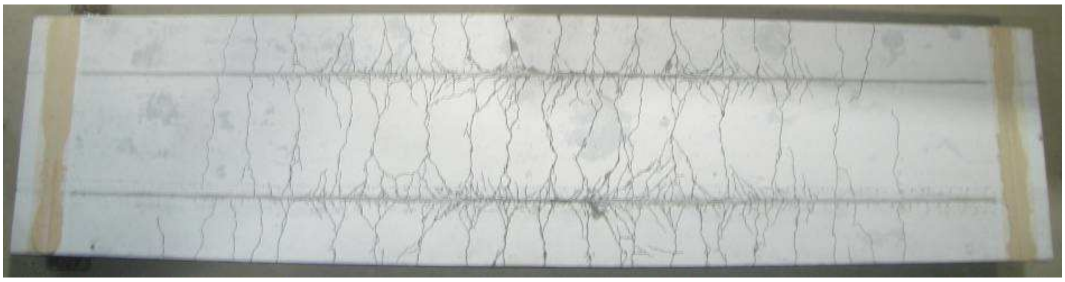
Slab	Service		Yielding		Maximum	
	$F_{serv.}$ (kN)	$\delta_{Fserv.}$ (mm)	F_{sy} (kN)	δ_{Fsy} (mm)	F_{max} (kN)	δ_{Fmax} (mm)
SREF	15.89	9.60	19.00	14.81	22.60	158.15
S2L-0	19.76	9.60	29.52	20.63	51.80	85.90
S2L-20	24.65	9.60	35.66	20.16	53.33	63.33
S2L-40	34.76	9.60	45.65	17.86	56.90	42.29

3.2 Failure modes

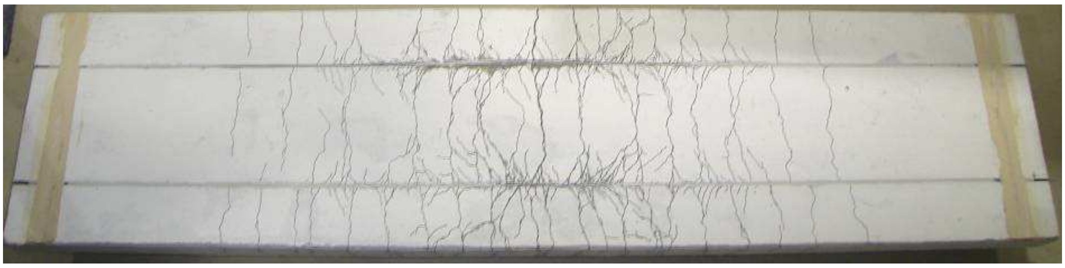
Fig. 6 shows the final crack pattern of the tested RC slabs. As this figure shows, strengthening RC slabs with NSM CFRP laminates has increased the number of cracks, and has decreased both the distance between cracks and crack width. When the final crack pattern of the NSM slabs is compared it is possible to conclude that the length of the slab's cracked band has decreased with the increase of the prestress level.



Non-strengthened RC slab (SREF slab)



RC slab strengthened with non-prestressed CFRP laminates (S2L-0 slab)

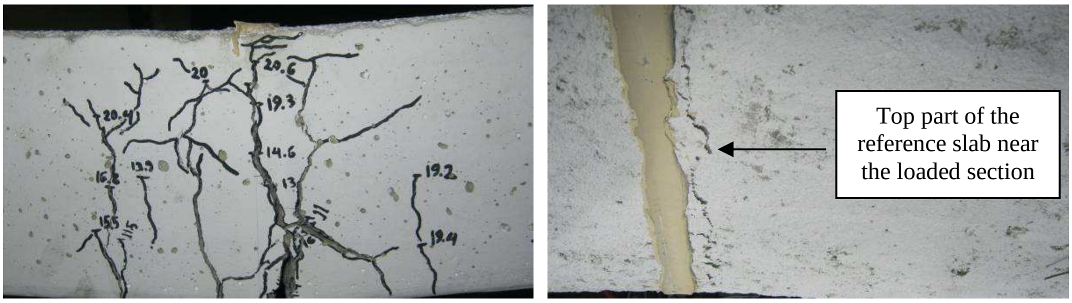


RC slab strengthened with prestressed CFRP laminates - 20% (S2L-20 slab)

RC slab strengthened with prestressed CFRP laminates - 40% (S2L-40 slab)

Figure 6: Cracking patterns for tested slabs.

Two types of failure modes occurred in the tested RC slabs. One type of failure mode occurred in the reference slab, and consisted on the concrete crushing after the yielding of the tensile steel reinforcements (see Fig. 7a). The other type of failure mode occurred in all the strengthened slabs, and was characterized by the rupture of the CFRP (see Fig. 7b) after the yielding of the tensile steel reinforcements.



a) Concrete crushing in the reference RC slab

b) Rupture of the CFRP in the slabs strengthened with NSM CFRP laminates

Figure 7: Failure modes of the tested RC slabs.

3.3 Strains in the CFRP

The maximum values of strain recorded in strain gauges installed in the CFRP laminates up to the maximum load (F_{max}) of the slabs are indicated in the column "Total" of the Table 4. Each of these values is the addition of the strain at the end of the prestress phase (column "Prestressing") with the maximum strain registered in the loading phase of the slab up to its F_{max} (column "Test"). The maximum values of strain measured in the CFRP laminates (column "Total"), namely in the SG-L2, are quite close to the ultimate tensile strain of the CFRP, justifying the failure mode of the strengthened slabs and the high effectiveness of the NSM technique for the flexural strengthening of RC slabs.

Table 4: Maximum values of strain recorded in CFRP laminates's strain gauges up to the maximum load of the slabs.

Slab	SG-L1(‰)			SG-L2(‰)			SG-L3(‰)		
	Prestressing	Test	Total	Prestressing	Test	Total	Prestressing	Test	Total
S2L-0	-	13.90	13.90	-	15.03	15.03	-	3.95	3.95
S2L-20	2.68	11.96	14.64	3.34	11.86	15.20	2.74	2.36	5.10
S2L-40	6.45	9.33	15.78	6.93	9.19	16.12	6.41	1.53	7.94

3.4 Effect of the prestress

To evaluate the effect of prestress level of CFRP laminates on the overall flexural behavior of RC slabs, the values of forces and corresponding deflection of the strengthened prestressed slabs are compared with the reference slab. The results of this comparison are indicated in Table 5, where the force value at serviceability and ultimate conditions (F_{serv} and F_{max}) of the reference slab, as well as the deflection at maximum force (δ_{Fmax}) of this slab are adopted for comparison purposes. Based on these results, strengthening with 0%, 20% and 40% prestressed laminates has provided an increase of, respectively, 24.35%, 55.13% and 118.75% in service load, and an increase of, respectively, 129.20%, 135.97% and 151.77% in maximum load. Therefore, by strengthening the RC slabs with prestressed NSM CFRP laminates has increased the load carrying capacity of this type of structures for both serviceability and ultimate limit states. However, by strengthening with 0%, 20% and 40% prestressed laminates, has decreased, respectively, 45.68%, 59.96% and 73.26% the maximum deflection, leading to a reduction of ductility with the increase of the prestress level applied to the CFRP laminates.

Table 5: Comparison of the results with the reference slab.

Slab	Increasing $F_{serv.}$ than the reference slab (%)	Increasing F_{max} than the reference slab (%)	Decreasing δ_{Fmax} than the reference slab (%)
S2L-0	24.35	129.20	45.68
S2L-20	55.13	135.97	59.96
S2L-40	118.75	151.77	73.26

4. CONCLUSIONS

By carrying out an experimental program, the influence of the prestressed level applied to CFRP laminates in the behavior of RC slabs flexurally strengthened with NSM technique was investigated. From the obtained experimental results it can be concluded that:

- Regardless the prestress level of the CFRP laminates, the NSM technique with CFRP laminates is highly effective for the flexural strengthening of RC slabs. The adopted CFRP flexural strengthening configuration provided an increase in terms of maximum load that ranged between 129% and 152% of the maximum load of the reference RC slab.
- Strengthening RC slabs with prestressed NSM CFRP laminates resulted in a significant increase of load carrying capacity at serviceability and ultimate limit states. By applying 20% of prestressing in the NSM CFRP laminates, the service and ultimate loads have increased, respectively, 55% and 136% the corresponding values of the reference slab. With applying 40% of prestressing, the service and ultimate loads have increased, respectively, 119% and 152% the corresponding values of the reference slab.
- By increasing the prestress level in the NSM CFRP laminates the overall flexural behavior of the slabs at service and ultimate states has improved, but the maximum deflection at the failure of the slabs has decreased with the increase of the prestress level.
- Regardless the prestress level applied to the CFRP laminates, all the strengthened slabs failed due to rupture of the laminates after yielding of the tension steel reinforcement. This failure mode proved the high effectiveness of the NSM technique for the flexural strengthening of RC slabs.

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REFERENCES

[1] Carolin, A., "*Carbon fibre reinforced polymers for strengthening of structural elements*." Doctoral Thesis, Division of Structural Engineering, Luleå University of Technology, Lulea, Sweden, 190 pp. (2003).

[2] El-Hacha, R. and Riskalla, S.H., "*Near-surface-mounted fiber-reinforced polymer reinforcements for flexural strengthening of concrete structures*", ACI Structural Journal, 101(5), 717-726 (2004).

[3] Barros, J.A.O. and Fortes, A.S., "*Flexural strengthening of concrete beams with CFRP laminates bonded into slits*", Journal Cement and Concrete Composites, 27(4) p. 471-480 (2005).

[4] Barros, J.A.O., Dias, S.J.E. and Lima J.L.T., "*Efficacy of CFRP-BASED techniques for the flexural and shear strengthening of concrete beams*", Journal Cement & Concrete Composites, Volume 29, Issue 3, March, pp. 203-217 (2007).

[5] Kotynia, R., "*Analysis of the flexural response of NSM FRP-strengthened concrete beams*", 8th International Symposium on Fiber Reinforced Polymer (FRP) Reinforcement for Concrete Structures (FRPRCS-8), Patras, Greece, July 16-18 (2007).

[6] Bonaldo, E., "*Composite materials and discrete steel fibres for the strengthening of thin concrete structures*", PhD Thesis, Department of Civil Engineering, University of Minho (2008).
[7] EN 206-1, *"Concrete - Part 1: Specification, performance, production and conformity."* European standard, CEN, 69 pp. (2000).
[8] EN 10002-1, *"Metallic materials - Tensile testing. Part 1: Method of test (at ambient temperature)"*, European Standard, CEN, Brussels, Belgium, 35 pp. (1990).
[9] ISO 527-5, *"Plastics - Determination of tensile properties - Part 5: Test conditions for unidirectional fibre-reinforced plastic composites"*, International Organization for Standardization (ISO), Geneva, Switzerland, 9 pp. (1997).
[10] Costa, I.G. and Barros, J.A.O., "Assessment of the long term behavior of structural adhesives in the context of NSM flexural strengthening technique with prestressed CFRP laminates", submitted to the 11th International Symposium on Fiber Reinforced Polymer (FRP) Reinforcement for Concrete Structures (FRPRCS-11), Guimarães (2013).
[11] ISO 527-2, "Plastics - Determination of tensile properties - Part 2: Test conditions for moulding and extrusion plastics" International Organization for Standardization, 1993.
[12] EN 1992-1-1, "*Eurocode2: Design of Concrete Structures Parte 1-1: General Rules for Buildings*", CEN, Brussels, Belgium, (2004).